OBSERVATIONS OF SOLAR-LIKE OSCILLATIONS

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ABSTRACT

There has been tremendous progress in observing oscillations in solar-type stars. In a few short years we have moved from ambiguous detections to firm measurements. We review the recent results, most of which have come from high-precision Doppler measurements. We also review briefly the results on giant and supergiant stars and the prospects for the future.

Key words: stellar oscillations.

1. MAIN-SEQUENCE AND SUBGIANT STARS

There has been tremendous progress in observing oscillations in solar-type stars, lying on or just above the Main Sequence. In a few short years we have moved from ambiguous detections to firm measurements. Most of the recent results have come from high-precision Doppler measurements using spectrographs such as CORALIE, HARPS, UCLES and UVES (see Fig. 1 for an example). The best data have be obtained from two-site campaigns, although single-site observations are also being carried out. Meanwhile, photometry from space gives a much better observing window than is usually achieved from the ground but the signal-to-noise is poorer. The WIRE and MOST missions have reported oscillations in several stars, although not without controversy, as discussed below.

The following list includes all recent observations of main-sequence and subgiant stars of which we are aware. The list is ordered according to decreasing stellar density (i.e., decreasing large frequency separation, $\Delta\nu$):

- τ Cet (G8 V): this star was observed with HARPS by T. C. Teixeira et al. (in prep.)
- 70 Oph A (K0 V): this is the main component of a spectroscopic visual binary (the other component is K5 V). It was observed over 6 nights with HARPS by Carrier & Eggenberger [19], who found $\Delta\nu = 162\,\mu$Hz but were not able to give unambiguous mode identifications from these single-site data.
- α Cen A and B (G2 V and K1 V): see Sec. 1.1.
- μ Ara (G3 V): this star has multiple planets. Oscillations were measured over 8 nights using HARPS by Bouchy et al. [11] (see Fig. 1) and the results were modelled by Bazot et al. [3]. They found $\Delta\nu = 90\,\mu$Hz and identified over 40 frequencies, with possible evidence for rotational splitting.
- HD 49933 (F5 V): this is a potential target for the COROT space mission and was observed over 10 nights with HARPS by Mosser et al. [39]. They reported a surprisingly high level of velocity variability on timescales of a few days. This was also present as line-profile variations and is therefore presumably due to stellar activity. The observations showed excess power from p-mode oscillations and the authors determined the large separation ($\Delta\nu = 89\,\mu$Hz) but were not able to extract individual frequencies.
- β Vir (F9 V): oscillations in this star were detected in a weather-affected two-site campaign with ELODIE and FEROS by Martić et al. [37]. Subsequently, Carrier et al. [21] used CORALIE with good weather but a single site, and reported 31 individual frequencies. Those results were modelled by Eggenberger & Carrier [26], who also reported tentative evidence for rotational splittings. The large separation is 72 μHz.
- Procyon A (F5 IV): see Sec. 1.3.
- β Hyi (G2 IV): oscillations were detected in β Hyi in 2001 using UCLES [6] and CORALIE [17]. This star was the target for a two-site campaign in 2005, with HARPS and UCLES, that resulted in the clear detection of mixed modes (Bedding et al., in prep.). The large separation is 57.5 μHz.
- δ Eri (K0 IV): Carrier et al. [16] observed this star over 12 nights in 2001 with CORALIE and found a large separation of 44 μHz.
- η Boo (G0 IV): see Sec. 1.2.
- ν Ind (G0 IV): this a metal-poor subgiant ([Fe/H] $= -1.4$) which was observed from two sites using UCLES and CORALIE. The large separation of 24 μHz, combined with the position of the star in the H-R diagram, indicated that the star has a low mass a low mass ($0.85 \pm 0.04\,M_\odot$) and is at least

9 Gyr old [5]. Further analysis is underway (Carrier et al., in prep.).

1.1. α Cen A and B

On the main-sequence, the most spectacular results have been obtained for the α Cen system. The clear detection of p-mode oscillations in α Cen A by Bouchy & Carrier [12] using the CORALIE spectrograph represented a key moment in this field. This was followed by a dual-site campaign on this star with UVES and UCLES [15] that yielded more than 40 modes, with angular degrees of $l = 0$ to 3 [10]. The mode lifetime is about 2–4 days and there is now evidence of rotational splitting from photometry with the WIRE satellite analysed by Fletcher et al. [27] (see Fig. 2) and also from ground-based spectroscopy with HARPS [2].

Meanwhile, oscillations in the B component were detected from single-site observations with CORALIE by Carrier & Bourban [18]. Dual-site observations with UVES and UCLES (see Fig. 3) allowed measurement of nearly 40 modes and of the mode lifetime [34].

We have previously pointed out [8] that the power spectrum of Procyon appears to show a dip at 1.0 mHz that is apparently consistent with the theoretical models of Houdek et al. [31]. A similar dip for low-mass stars was also discussed by Houdek at this conference (see also Chaplin et al. [22]), and the observations of α Cen B in Fig. 3 do indeed show such a dip, although not at the frequency indicated by the models. It seems that the shape of the oscillation envelope is an interesting observable that can be extracted from the power spectrum and compared with theoretical models.

1.2. η Boo

This star, being the brightest G-type subgiant in the sky, remains a very interesting target. The claimed detection of oscillations almost decade ago by Kjeldsen et al. [35], based on fluctuations in Balmer-line equivalent-widths, has now been confirmed by further equivalent-width and velocity measurements by the same group [33] and also by independent velocity measurements with the CORALIE spectrograph [20]. With the benefit of hindsight, we can now say that η Boo was the first star for which the large separation and individual frequencies were measured. However, there is still disagreement on some of the individual frequencies, which reflects the subjective way in which genuine oscillation modes must be chosen from noise peaks and corrected for daily aliases. Fortunately, the large separation is $\Delta\nu = 40\,\mu$Hz, which is half way between integral multiples of the 11.57-μHz daily splitting (40/11.57 = 3.5). Even so, daily aliases are problematic, especially because some of the modes in η Boo appear to be shifted by avoided crossings.

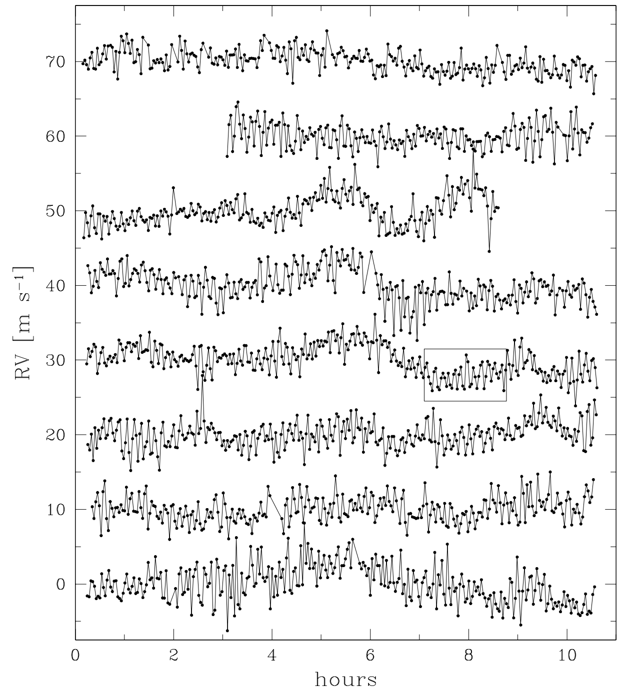

Figure 1. Radial velocity time series of the star μ Ara made over 8 nights with the HARPS spectrograph. Figure from Bouchy et al. [11].

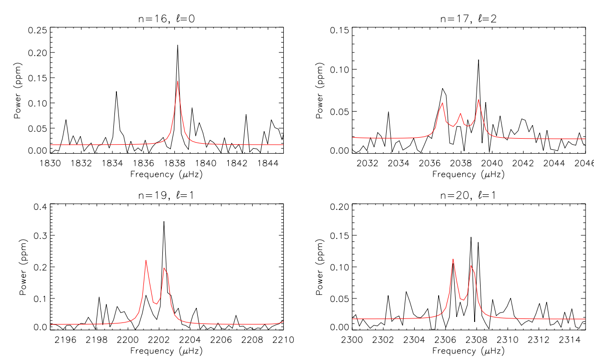

Figure 2. Four oscillation modes in α Cen A from the WIRE power spectrum, with fits that indicate the linewidth and rotational splitting. Figure from Fletcher et al. [27].

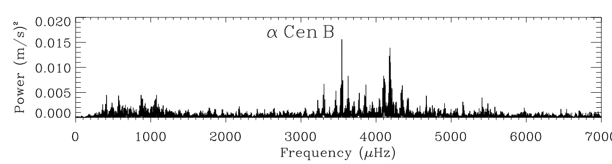

Figure 3. Power spectrum of α Cen B from velocity observations. Note the double-humped structure with a central dip. Figure from Kjeldsen et al. [34].

The first spaced-based observations of η Boo, made with the MOST satellite, have generated considerable controversy. Guenther et al. [29] showed an amplitude spectrum (their Fig. 1) that rises towards low frequencies in a fashion that is typical of noise from instrumental and stellar sources. However, they assessed the significance of individual peaks by their strength relative to a fixed horizontal threshold, which naturally led them to assign high significance to peaks at low frequency. They did find a few peaks around 600 μHz that agreed with the ground-based data, but they also identified eight of the many peaks at much lower frequency (130–500 μHz), in the region of rising power, as being due to low-overtone p-modes. Those peaks do line up quite well with the regular 40 μHz spacing, but extreme caution is needed before these peaks are accepted as genuine. This is especially true given that the orbital frequency of the spacecraft (164.3 μHz) is, by bad luck, close to four times the large separation of η Boo (164.3/40 = 4.1). Models of η Boo based on the combination of MOST and ground-based frequencies have been made by Straka et al. [41].

1.3. Procyon

Procyon has long been a favourite target for oscillation searches. There have been at least eight separate velocity studies, mostly single-site, that have reported a hump of excess power around 0.5–1.5 mHz. See Martić et al. [36], Bouchy et al. [13] and Claudi et al. [24] for the most recent examples. However, there is not yet agreement on the oscillation frequencies, although a consensus is emerging that the large separation is about 55 μHz.

This star generated controversy when MOST data reported by Matthews et al. [38] failed to reveal oscillations that were claimed from ground-based data. However, Bedding et al. [9] argued that the MOST non-detection was consistent with the ground-based data. Using space-based photometry with the WIRE satellite, Bruntt et al. [14] extracted parameters for the stellar granulation and found evidence for an excess due to p-mode oscillations.

A multi-site campaign on Procyon is being organised for January 2007, which will be the most extensive velocity campaign so far organised on a solar-type oscillator.

2. G AND K GIANTS

There have been detections of oscillations in red giant stars with oscillation periods of 2–4 hours. Ground-based velocity observations were presented at the last SOHO/GONG meeting by Barban et al. [1], who used CORALIE and ELODIE spectrographs to find excess power and a possible large separation for both ϵ Oph (G9 III) and η Ser (K0 III). The data for ϵ Oph have now been published by De Ridder et al. [25]. Hekker et al. [30] have analysed the line-profile variations and found evidence for non-radial oscillations.

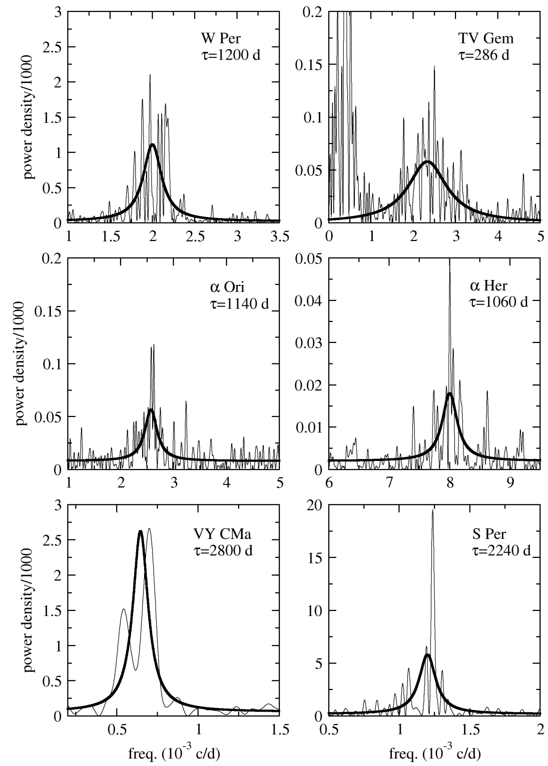

Figure 4. Power spectra of red supergiants from visual observations (thin lines) with Lorentzian fits (thick lines). Figure from Kiss et al. [32].

Meanwhile, earlier observations of oscillations in ξ Hya (G7 III) by Frandsen et al. [28] have been further analysed by Stello et al. [40], who found evidence that the mode lifetime is only about 2 days. If confirmed, this would significantly limit the the prospects for asteroseismology on red giants.

3. RED GIANTS AND SUPERGIANTS

If we define solar-like oscillations to be those excited and damped by convection then we expect to see such oscillations in all stars on the cool side of the instability strip. Evidence for solar-like oscillations in semiregular variables, based on visual observations by groups such as the AAVSO, has already been reported. This was based on the amplitude variability of these stars [23] and on the Lorenztian profiles of the power spectra [4, 7].

Recently, Kiss et al. [32] used visual observations from the AAVSO to show that red supergiants, which have masses of 10–30$M_\odot$, also have Lorenztian profiles in their power spectra (see Fig. 4).

4. THE FUTURE

In the future, we expect further ground-based observations using Doppler techniques (for example, a multi-site campaign on Procyon has been organized for January 2007). The new spectrograph SOPHIE at l'Observatoire de Haute-Provence in France should be operating very soon (`http://www.obs-hp.fr/`). From space, the WIRE and MOST satellites continue to return data and we look forward with excitement to the expected launches of COROT (November 2006) and Kepler (2008).

Looking further ahead, the SIAMOIS spectrograph is planned for Dome C in Antarctica (Seismic Interferometer Aiming to Measure Oscillations in the Interior of Stars; see `http://siamois.obspm.fr/`). Finally, there are ambitious plans to build SONG (Stellar Oscillations Network Group), which will be a global network of small telescopes equipped with high-resolution spectrographs and dedicated to asteroseismology and planet searches (see `http://astro.phys.au.dk/SONG`).

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